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13. ABSTRACT (Maximum 200 words) This report gives an overview of the experimental and theoretical research supported by ONR grant N00014-89-J-1714 from 1989 to 1995. The research focused on waves, transport, and equilibrium of magnetically confined single-species plasmas. Two new apparatuses were built: a laser-diagnosed ion apparatus targeted towards "test-particle" measurements of cross-field transport from long-range ion-ion collisions; and a camera-diagnosed electron apparatus which gives quantitative data on 2-dimensional fluid instabilities, vortices, turbulence and relaxation processes. Theory work provided support for the experiments, and developed several fundamental plasma effects, including rotational pumping transport, a 2D stability theorem, waves in finite-size ion plasmas, and the structure of ion crystals. These results have been published in 57 journal articles and 5 Ph.D. theses.				
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Dear Chuck,

Enclosed are 3 copies of the Final Technical Report on our ONR Grant N00014-89-J-1714.
Please let me know if you need further information.

Sincerely,

A handwritten signature in cursive script, appearing to read "Fred", is written over a horizontal line.

C. Fred Driscoll

CFD/jc

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Final Technical Report

"Pure Electron Plasmas Near Thermal Equilibrium"

1989 — 1996

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ONR support has enabled a highly productive program of experiments and theory on waves, transport, and equilibrium in single species plasmas. These single species plasmas are unique in that they can relax to global thermal equilibrium while confined in a simple cylindrical trap. In practice, this means that incisive quantitative measurements can be made on a variety of fundamental plasma processes, for direct comparison to theory predictions.

During this grant, two new apparatuses were developed and are now fully productive: a new laser-diagnosed ion plasma apparatus, called "IV," which allows quantitative measurement of test particle transport; and a new camera-diagnosed electron apparatus, "CamV," which gives high resolution images of 2D cross-field flows. Additionally, experiments were continued on the existing electron plasma containment apparatus "EV." Theory work developed fundamental ideas of waves, transport, and equilibrium in these systems, and supported the experiments.

In general, we have sought to obtain tests of plasma theory under the simplest possible circumstances we can devise; and, when the theory is inadequate, to develop it further. We now understand in detail some of the important processes which transport particles, energy and momentum across magnetic fields. Further, the wide range of parameters available in these systems has allowed us to understand which processes dominate in various parameter regimes.

The scientific results are fully described in the journal articles and Ph.D. theses. Here we give a brief overview and reference to the papers.

The electron experiments and theory work have focused on the rapid transport associated with 2D fluid vortices, instabilities, and turbulence. The 2D drift-Poisson equations governing the magnetized electron columns are mathematically identical to the 2D Euler equation governing inviscid, incompressible fluids such as water. Our initial experiments on nonlinear vortex dynamics and merger established that the electron columns evolve as fluid vortices, and are probably the most precise tests of fundamental fluid processes [1,4-7,9,15-16]. We have recently developed a technique to track the positions of the individual vortices using only received signals on the walls, and we believe this will enable even more quantitative understanding of processes affecting vortex dynamics [12].

Experiments on instability transport began with investigation of hollow electron columns which exhibit "diocotron" mode shear instabilities, which are the plasma analogue of Kelvin-Helmholtz fluid instabilities [2-3,8]. The instability undergoes nonlinear saturation with the formation of vortices, then the vortices move chaotically and appear as turbulent noise, and finally the noise decays leaving a reasonably quiet 2D quasi-equilibrium [17-18,23-28]. The collisional (or "viscous") transport to 3D thermal equilibrium then occurs on a much longer time scale.

Our recent experiments have provided insights into processes contributing to the relaxation of 2D fluid turbulence. Experimental characterization of "beat wave damping" established that this nonlinear process will symmetrize isolated vortices even in the absence of viscosity [14]. This process had not been considered in the fluids community, and is precluded in "contour dynamics" simulations. Our experiments on the relaxation of turbulence demonstrated that minimization of enstrophy gives a quantitative prediction of the relaxed meta-equilibrium for moderate energy initial conditions, providing a substantial challenge to theory [23].

Most surprisingly, recent experiments on CamV have shown that relaxation processes can be totally arrested by the formation of "vortex crystal" states, where the turbulent vortices have settled into a geometric pattern which lasts for up to 10^4 rotation times [26]. Here, the challenge to theory is to understand how the intense vortices give energy to the background of diffuse vorticity, and to understand whether the existence of these vortex lattice states fundamentally affects the chaotic dynamics and merger processes by which turbulence relaxes.

We have also extended the theory of the stability of these 2D plasmas. Our new 2D stability theorem provides a basis for understanding the longevity of various equilibria (observed by Fajans and others) when the confinement boundaries are not axisymmetric [9,10]. The traditional stability theorem of Davidson and Krall applies only to symmetric equilibria, but we find that the asymmetric equilibria are stable if the electrostatic energy is a *maximum* with respect to nearby states that are accessible under incompressible flow. This work has now been generalized to toroidal geometry [13].

The IV apparatus is now fully operational, equipped with two tuneable lasers. The laser-induced-fluorescence diagnostic routinely gives the temperature, density, and rotation velocity profiles of the Mg^+ ions, and the plasmas can be simultaneously cooled or manipulated with the second laser. The ion plasmas have an "anomalous" loss time of thousands of seconds, which is close to that expected from a dependence on the ratio of axial bounce time to rotation time and a theoretical mass scaling [50].

Interestingly, we have established that the ion plasma can be contained effectively "forever" by applying a rotating electric asymmetry to the walls [51]. In practice, the same ions are now contained with the same density and temperature profiles for up to 2 weeks, allowing accurate experiments. Further, we believe this technique may be very useful for other containment devices.

Most significantly, we have now demonstrated that the LIF diagnostics can measure test particle transport with time scales from $0.1\text{-}10^3$ seconds. Here, the atomic spins of certain ions are "tagged," and these particles are tracked as they move across the magnetic field. This gives unprecedented ability to quantify the underlying transport processes for comparison to theory,

especially since the measurements can be made repeatedly on a plasma which macroscopically is not varying with time. The enhanced transport expected from our theories is clearly being seen.

Our early experiments on the EV apparatus first observed the transport to confined 3D thermal equilibrium states. In the course of these experiments, we realized that traditional transport theory was implicitly based on an ordering of plasma parameters which does not apply to magnetically confined single-species plasmas. We developed a new transport theory for this case, which predicts that the rate of transport to thermal equilibrium is much faster and that the physics is very different. Essentially, the shear viscosity of the electron fluid is much greater than naively expected, and this viscosity may even be non-local. Understanding this transport would be a major contribution to basic plasma physics, and data now being taken from IV and EV will allow us to do so.

In other experiments on the cryogenic CV apparatus, we have measured the compressional, or bulk viscosity of the electron fluid [32,33,35]. Here, the length of a flux tube of plasma varies periodically as the plasma rotates, and compressional viscosity acts on this "rotational pumping" to cause relaxation towards 3D thermal equilibrium [31]. Quantitative agreement with theory is obtained over many decades in plasma parameters, making this the best-understood example of asymmetry-induced particle transport. This understanding is now being applied to other transport situations [34].

Ion-cyclotron wave experiments on IV revealed that the ion plasma contains both Mg^+ and Mg^{++} , and that significant cyclotron wave frequency shifts occur due to the presence of the second species [52,53]. The general signature is similar to that recently obtained by Gould for electron plasmas: an $l=1$ mode is observed slightly below Ω_c , and $l=2$ and $l=3$ modes are observed somewhat higher than Ω_c . Our multi-species analysis explains the $l=1$ downshift in terms of the $\text{Mg}^{++}/\text{Mg}^+$ ratio and the radius of the plasma, and thus can be used as a diagnostic for these parameters. We believe these experiments may contribute to understanding this ion cyclotron resonance technique for chemical mass analysis.

Many physics applications utilize ion plasmas at ultra-low temperatures, where liquid or crystal states are observed, and recent theory work has contributed substantially to our understanding of these states. Surface effects change the crystal structure when the dimensions of the crystal are less than a few 10 's of interparticle spacings [36-38,40], which is typically the case in the experiments. As the external potentials vary and the overall shape of the plasma changes, the crystal undergoes structural transitions [44,45]. One important limit is the case where the charges are squeezed onto the trap axis by the external forces, forming a 1D Coulomb chain. These chains have been realized in experiments on storage rings and in Paul traps.

Thermal relaxation in strongly correlated plasmas is also being studied. For 1D chains in storage rings, the temperatures parallel and perpendicular to the chain axis relax towards one another at an exponentially slow rate set by the breaking of a many-particle adiabatic invariant [30]. A similar result has recently been predicted for the equilibration of transverse and parallel temperatures in a strongly magnetized strongly correlated plasma [29]. This extends our earlier thermal relaxation work for strongly magnetized plasmas into the regime of strong correlation.

The collective electrostatic modes of cold nonneutral plasmas are also a subject of great current interest. We have developed an analytic theory that predicts the mode frequencies for such plasmas, including the effect of strong correlation on the modes [39,41-43,47-49]. Excitation of the modes can provide a useful nondestructive diagnostic of plasma properties such as density and plasma shape. Modes have also been implicated in transport processes leading to loss of the plasma and limits on the density. Our theoretical work on strong correlation effects on the mode frequencies may also provide an experimental method to determine the shear and bulk moduli of a strongly correlated plasma, which is of interest to a range of disciplines including astrophysics and condensed matter physics.

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Journal Articles

2D Fluid Dynamics

1. K. S. Fine, C. F. Driscoll and J. H. Malmberg, "Measurements of a Nonlinear Diocotron Mode in Pure Electron Plasmas," *Phys. Rev. Lett.* **63**, 2232 (1989).
2. C. F. Driscoll, "Observation of an Unstable $l = 1$ Diocotron Mode on a Hollow Electron Column," *Phys. Rev. Lett.* **64**, 645 (1990).
3. R. A. Smith and M. N. Rosenbluth, "Algebraic Instability of Hollow Electron Columns and Cylindrical Vortices," *Phys. Rev. Lett.* **64**, 649 (1990).
4. C. F. Driscoll and K. S. Fine, "Experiments on Vortex Dynamics in Pure Electron Plasmas," *Phys. Fluids B* **2**, 1359 (1990).
5. K. S. Fine, C. F. Driscoll, J. H. Malmberg and T. B. Mitchell, "Measurements of Symmetric Vortex Merger in Pure Electron Plasmas," *Phys. Rev. Lett.* **67**, 588 (1991).
6. K. S. Fine, "Simple Theory of a Nonlinear Diocotron Mode," *Phys. Fluids B* **4**, 3981-3984 (1992).
7. C. F. Driscoll, "Wave and Vortex Dynamics in Pure Electron Plasmas," in *Research Trends in Physics* (V. Stefan, editor), 454. New York: American Institute of Physics (1992).
8. R. A. Smith, "Effects of Electrostatic Confinement Fields and Finite Gyroradius on an Instability of Hollow Electron Columns," *Phys Fluids B* **4**, 287 (1992).
9. R.A. Smith, T.M. O'Neil, S.M. Lund, J. J. Ramos, R.C. Davidson, "Comment on the Stability Theorem of Davidson and Lund," *Physics of Fluids B* **4**, 1373 (1992).
10. T. M. O'Neil and R. A. Smith, "Stability Theorem for Off-Axis States of a Non-neutral Plasma Column," *Phys. Fluids B* **4**, 2720 (1992).
11. T. B. Mitchell, C. F. Driscoll and K. S. Fine, "Experiments on Stability of Equilibria of Two Vortices in a Cylindrical Trap," *Phys. Rev. Lett.* **71**, 1371 (1993).
12. J. B. Kadtko, T. B. Mitchell, C. F. Driscoll and K. S. Fine, "Re-Constructing Chaotic Vortex Trajectories from Plasma Data," in *Current Topics in Astrophysical and Fusion Plasma Research* (M. F. Heyn, W. Kernbichler and H. K. Biernat, Eds.), 1. dbv-Verlag Graz, Publishers (1994).
13. T. M. O'Neil and R. A. Smith, "Stability Theorem for a Single Species Plasma in a Toroidal Magnetic Configuration," *Phys. Plasmas* **1**, 2430 (1994).
14. T. B. Mitchell and C. F. Driscoll, "Symmetrization of 2D Vortices by Beat-Wave Damping," *Phys. Rev. Lett.* **73**, 2196 (1994).
15. T. B. Mitchell and C. F. Driscoll, "Electron Vortex Orbits and Merger," to appear in *Phys. Fluids*.

16. C. F. Driscoll, "Wave and Vortex Dynamics in Pure Electron Plasmas," to appear in AIP series.

2D Fluid Turbulence and Statistics

17. C. F. Driscoll, J. H. Malmberg, K. S. Fine, R. A. Smith, X.-P. Huang and R. W. Gould, "Growth and Decay of Turbulent Vortex Structures in Pure Electron Plasmas," in *Plasma Physics and Controlled Nuclear Fusion Research 1988*, Vol. 3, 507-514. Vienna: IAEA (1989).
18. C. F. Driscoll, R. A. Smith, X.-P. Huang and J. H. Malmberg, "Growth and decay of vortex structures in pure electron plasmas," in *Structures in Confined Plasmas—Proc. of Workshop of U.S.-Japan Joint Institute for Fusion Theory Program*, Report No. NIFS-PROC-2, 69-76. Nagoya: National Institute for Fusion Science (1990).
19. R. A. Smith, "Phase-Transition Behavior in a Negative-Temperature Guiding-Center Plasma," *Phys. Rev. Lett.* **63**, 1479 (1989).
20. R. A. Smith and T. M. O'Neil, "Nonaxisymmetric Thermal Equilibria of a Cylindrically Bounded Guiding Center Plasma or Discrete Vortex System," *Phys. Fluids B* **2**, 2961 (1990).
21. R. A. Smith, "Maximization of Vortex Entropy as an Organizing Principle in Intermittent, Decaying, Two-Dimensional Turbulence," *Phys. Rev. A* **43**, 1126 (1991).
22. R. A. Smith, "Effectively Nonergodic Behavior of Guiding-Center and Discrete-Vortex Systems," in *Research Trends in Physics: Chaotic Dynamics and Transport in Fluids and Plasmas* (I. Prigogine et al., Eds.), 396. New York: American Institute of Physics (1993).
23. X.-P. Huang and C. F. Driscoll, "Relaxation of 2D Turbulence to a Metaequilibrium Near the Minimum Enstrophy State," *Phys. Rev. Lett.* **72**, 2187 (1994).
24. C. F. Driscoll, T. B. Mitchell, X.-P. Huang, and K. S. Fine, "Turbulence and Relaxation in 2D Non-Neutral Plasmas," in *Non-Neutral Plasma Physics II*, AIP Conference Proceedings #331 (J. Fajans and D.H.E. Dubin, eds.), 38. New York: AIP press (1995).
25. X.-P. Huang, K. S. Fine and C. F. Driscoll, "Coherent Vorticity Holes from 2D Turbulence Decaying in a Background Shear Flow," *Phys. Rev. Lett.* **74**, 4424 (1995).
26. K. S. Fine, W. G. Flynn, A. C. Cass and C. F. Driscoll, "Relaxation of 2D Turbulence to Vortex Crystals," *Phys. Rev. Lett.* **75**, 3277 (1995).
27. C. F. Driscoll, K. S. Fine, X.-P. Huang, T. B. Mitchell, A. C. Cass and T. M. O'Neil, "Vortices, Holes, and Turbulent Relaxation in Sheared Electron Columns, in Proc. of 15th Intl. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA.
28. C. F. Driscoll, K. S. Fine, X.-P. Huang, T. B. Mitchell and B. P. Cluggish, "Vortices and Turbulent Relaxation in Magnetized Electron Columns," to appear in Proc. of Conf. on Transport, Chaos & Plasma Physics 2.

Collisional Transport

29. S.-J. Chen and D. H. E. Dubin, "Equilibration Rate of Spin Temperature in a Strongly Magnetized Pure Electron Plasma," *Phys. Fluids B* **5**, 691 (1993).
30. S.-J. Chen and D. H. E. Dubin, "Temperature Equilibration of a 1D Coulomb Chain and a Many-Particle Adiabatic Invariant," *Phys. Rev. Lett.* **71**, 2721 (1993).
31. S. Crooks and T. M. O'Neil, "Rotational Pumping and Damping of the $m = 1$ Diocotron Mode," *Phys. Plasmas* **2**, 355 (1995).
32. B. Cluggish and C. F. Driscoll, "Transport and Damping from Rotational Pumping in Magnetized Electron Plasmas," *Phys. Rev. Lett.* **74**, 4213 (1995).
33. B. P. Cluggish and C. F. Driscoll, "Measurement of Transport and Damping from Rotational Pumping," in *Non-Neutral Plasma Physics II*, AIP Conference Proceedings #331 (J. Fajans and D.H.E. Dubin, eds.), 14. New York: AIP press (1995).
34. S. M. Crooks and T. M. O'Neil, "Transport in a Toroidally Confined Pure Electron Plasma," submitted to *Phys. Plasmas*.
35. B. P. Cluggish and C. F. Driscoll, "Transport and Sawtooth Oscillations from Rotational Pumping of a Magnetized Electron Plasma," to appear in *Phys. Plasmas*.

Ion Plasmas and Crystals: Theory

36. D. H. E. Dubin, "Correlation Energies of Simple Bounded Coulomb Lattices," *Phys. Rev. A* **40**, 1140 (1989).
37. D. H. E. Dubin, "First-Order Anharmonic Correction for the Free Energy of a Coulomb Crystal in Periodic Boundary Conditions," *Phys. Rev. A* **42**, 4972 (1990).
38. R. Rafac, J. Schiffer, J. Hangst, D. Dubin and D. Wales, "Stable Configurations of Confined Cold Ionic Systems" *Proc. Natl. Acad. Sci. USA* **88**, 483 (1991).
39. D. H. E. Dubin, "Theory of Electrostatic Fluid Modes in a Cold Spheroidal Nonneutral Plasma," *Phys. Rev. Lett.* **66**, 2076 (1991).
40. D. H. E. Dubin and T. M. O'Neil, "Pure Ion Plasmas, Liquids and Crystals," in *Research Trends in Physics* (V. Stefan, editor), 460. New York: American Institute of Physics (1992).
41. J. J. Bollinger, D. J. Heinzen, F. L. Moore, W. M. Itano, D. Wineland, and D. H. E. Dubin, "Electrostatic Modes of Ion Trap Plasmas," *Phys. Rev. A* **48**, 525 (1993).
42. D. H. E. Dubin, "Equilibrium and Dynamics of Uniform Density Ellipsoidal Non-neutral Plasmas," *Phys. Fluids B* **5**, 295 (1993).
43. D. H. E. Dubin, "Normal Modes in a Cryogenic Pure Ion Plasma," in *Strongly Coupled Plasma Physics* (H. M. Van Horn and S. Ichimaru, Eds.), 399. New York: Univ. of Rochester Press (1993).
44. D. H. E. Dubin, "Theory of Structural Phase Transitions in a Trapped Coulomb Crystal," *Phys. Rev. Lett.* **71**, 2753 (1993).
45. D. H. E. Dubin and H. Dewitt, "Polymorphic Phase Transition for Inverse-Power-Potential Crystals Keeping the First-Order Anharmonic Correction to the Free Energy," *Phys. Rev. B*

49, 3043 (1994).

46. J. J. Bollinger, D. J. Wineland and D. H. E. Dubin, "Non-neutral Ion Plasmas and Crystals, Laser Cooling, and Atomic Clocks," *Phys. Plasmas* **1**, 1403 (1994).
47. D. H. E. Dubin, "Effect of Correlations on the Thermal Equilibrium and Normal Modes of a Nonneutral Plasma," to appear in *Phys. Rev. E* (1996).
48. D. H. E. Dubin and J. P. Schiffer, "Normal Modes of Cold Confined One-Component Plasmas," to appear in *Phys. Rev. E* (1996).
49. D. H. E. Dubin, "Correlation Effects on Static and Dynamic Properties of Nonneutral Plasmas," to appear in Proc. of Intl. Conf. on Physics of Strongly Coupled Plasmas.

Ion Plasmas: Experiments

50. F. Anderegg, X.-P. Huang, C. F. Driscoll, G. D. Severn, and E. Sarid, "Long Ion Plasma Confinement Times with a "Rotating Wall", in *Non-Neutral Plasma Physics II*, AIP Conference Proceedings #331 (J. Fajans and D.H.E. Dubin, eds.), 1. New York: AIP press (1995).
51. R. E. Pollock and F. Anderegg, "Spin-Up of an Electron Plasma—First Results," in *Non-Neutral Plasma Physics II*, AIP Conference Proceedings #331 (J. Fajans and D.H.E. Dubin, eds.), 139. New York: AIP press (1995).
52. E. Sarid, F. Anderegg, and C. F. Driscoll, "Cyclotron Modes of a Multi-Species Ion Plasma," in *Non-Neutral Plasma Physics II*, AIP Conference Proceedings #331 (J. Fajans and D.H.E. Dubin, eds.), 184. New York: AIP press (1995).
53. E. Sarid, F. Anderegg, and C. F. Driscoll, "Cyclotron Resonance Phenomena in a Non-Neutral Multispecies Ion Plasma," *Phys. Plasmas* **2**, 2895 (1995).

Miscellaneous

54. A. M. Dimits, L. L. LoDestro and D. H. E. Dubin, "Gyroaveraged equations for both the gyrokinetic and drift-kinetic regimes," *Phys. Fluids B* **4**, 274 (1992).
55. J. H. Malmberg, "Some Recent Results with Nonneutral Plasmas," in *Plasma Physics and Controlled Fusion* **34** (K. Lackner and W. Lindinger, Eds.), 1767. Pergamon Press (1992).
56. T. M. O'Neil, "Plasmas with a Single Sign of Charge (An Overview)," *Physica Scripta* **T59**, 341 (1995).
57. D. H. E. Dubin, "Nonlinear Debye Shielding in a Dusty Plasma," to appear in Proc. of Workshop on Physics of Dusty Plasmas, La Jolla.

Theses

58. B. R. Beck, "Measurement of the Magnetic and Temperature Dependence of the Electron-Electron Anisotropic Temperature Relaxation Rate" UCSD Ph.D. dissertation (1990).
59. T. B. Mitchell, "Experiments on Electron Vortices in Malmberg-Penning Trap," UCSD Ph.D. dissertation (1993).
60. X.-P. Huang, "Experimental Studies of Relaxation of Two-Dimensional Turbulence in Magnetized Electron Plasma Columns," UCSD Ph.D. dissertation (1993).

61. B. P. Cluggish, "Experiments on Asymmetry-Induced Particle Transport in Magnetized, Pure Electron Plasma Columns," UCSD Ph.D. dissertation (1995).
62. S. M. Crooks, "Rotational Pumping Transport in Magnetized, Non-Neutral Plasmas," UCSD Ph.D. dissertation (1995).

Invited Papers

63. C. F. Driscoll, "Experiments on Vortex Dynamics in Pure Electron Plasmas," *Bull. Am. Phys. Soc.* **34**, 2001 (1989).
64. D. H. E. Dubin and T. M. O'Neil, "Theory of Strongly-Correlated Pure Ion Plasmas in Penning Traps," in *Strongly Coupled Plasma Physics*, (S. Ichimaru, editor), Elsevier Science Pub. B.V./Yamada Science Foundation, 189-200 (1990).
65. D. H. E. Dubin, "Strongly Correlated Trapped Pure Ion Plasmas," to appear in *Proc. of 1989 International Conference on Plasma Physics*, New Delhi, India (1989).
66. T. M. O'Neil, "Plasmas with a Single Sign of Charge (A Review of Recent Theory and Experiment)," Sherwood Theory Conference, Williamsburg, VA (1990).
67. C. F. Driscoll, "Wave and Vortex Dynamics in Pure Electron Plasmas," Topical Conference on Research Trends in Nonlinear and Relativistic Effects in Plasmas, La Jolla, CA (1990).
68. D. H. E. Dubin and T. M. O'Neil, "Pure Ion Plasmas, Liquids and Crystals," Topical Conference on Research Trends in Nonlinear and Relativistic Effects in Plasmas, La Jolla, CA (1990).
69. D. H. E. Dubin and T. M. O'Neil, "Pure Ion Plasmas, Liquids and Crystals," Workshop on Nonlinear and Chaotic Phenomena in Plasma Solids and Fluids, Edmonton, Canada (1990).
70. C. F. Driscoll, "Wave and Vortex Dynamics in Pure Electron Plasmas," Topical Conference on Research Trends in Nonlinear and Relativistic Effects in Plasmas, La Jolla, CA (1990).
71. D. H. E. Dubin and T. M. O'Neil, "Pure Ion Plasmas, Liquids and Crystals," Topical Conference on Research Trends in Nonlinear and Relativistic Effects in Plasmas, La Jolla, CA (1990).
72. J. H. Malmberg, "Collisional Relaxation of an Anisotropic Temperature in a Pure Electron Plasma—Experiment and Theory" *Bull. Am. Phys. Soc.* **36**, 2271 (1991).
73. C. F. Driscoll, "Vortices and Transport in Pure Electron Plasmas," International Topical Conference on Research Trends in Chaotic Dynamics and Transport in Fluids and Plasmas, La Jolla, CA (1991).
74. J. H. Malmberg, "Some Recent Results with Nonneutral Plasmas," Plasma Physics 1992: Joint Conference of the 9th Kiev Intl. Conf. on Plasma Theory, 9th Intl. Congress on Waves and Instabilities in Plasmas, and 19th European Physical Society Conf. on Controlled Fusion and Plasma Physics (1992).
75. D. H. E. Dubin, "Normal Modes in a Cryogenic Pure Ion Plasma," Intl. Conf. on the Physics of Strongly Coupled Plasmas, Rochester, NY (1992).

76. C. F. Driscoll, "Experiments on 2D Vortices and Turbulence in Sheared Electron Columns," *Bull. Am. Phys. Soc.* **38**, 1933 (1993).
77. C. F. Driscoll, K. S. Fine, X.-P. Huang, T. B. Mitchell, A. C. Cass and T. M. O'Neil, "Vortices, Holes, and Turbulent Relaxation in Sheared Electron Columns, IAEA meeting, Seville (1994).
78. J. B. Kadtko, T. B. Mitchell, C. F. Driscoll and K. S. Fine, "Re-Constructing Chaotic Vortex Trajectories from Plasma Data," Proc. International Workshop on Plasma Physics, Pichl, Austria (1994).
79. T. M. O'Neil, "Plasmas with a Single Sign of Charge (An Overview)," Nobel Symposium, Lysekil, Sweden (1994).
80. C. F. Driscoll, "Vortices and Turbulent Relaxation in Magnetized Electron Columns," Third Intl. Workshop: Interrelationship between Plasma Experiments in the Laboratory and in Space, Pitlochry, Scotland (1995).
81. C. F. Driscoll, K. S. Fine, X.-P. Huang, T. B. Mitchell and B. P. Cluggish, "Vortices and Turbulent Relaxation in Magnetized Electron Columns," IAEA, Marseille (1995).
82. C. F. Driscoll, "Electron Plasmas as Simple Fluids: From Turbulence to Vortex Crystals to Thermal Equilibrium," *Bull. Am. Phys. Soc.* **40**, 1746 (1995).
83. B. P. Cluggish, "Transport and Sawtooth Oscillations from Rotational Pumping of a Magnetized Electron Plasma," *Bull. Am. Phys. Soc.* **40**, 1775 (1995).
84. D. H. E. Dubin, "Correlation Effects on Static and Dynamic Properties of Nonneutral Plasmas," Intl. Conf. on Physics of Strongly Coupled Plasmas, Binz, Germany (1995).
85. D. H. E. Dubin, "Nonlinear Debye Shielding in a Dusty Plasma," Workshop on Physics of Dusty Plasmas, La Jolla (1995).
86. D. H. E. Dubin, "Plasma Physics of Strong Correlation," Crystalline Beams and Related Issues Workshop, Erice, Italy (1995).